Effect of climate change on potential distribution of *Dactylorhiza hatagirea* (D. Don) Soó in the twenty-first century across the north-western Himalayas

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Abstract

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The populations of *Dactylorhiza hatagirea* are shrinking fast across the north-western Himalayas. Although the effects of contemporary anthropic factors on its distribution are well documented, the impacts of anticipated climate change have not been evaluated. In the present study, the maximum entropy modelling (MaxEnt) was used to quantify the impact of climate change on the distribution of *D. hatagirea* over the next 50 years under representative concentration pathways (RCP) 4.5 and 8.5, using ensemble mean of four general circulation models, *viz.* CCSM4, CNRM, MRI, and GFDL. The results exhibited a fairly good model performance, with *D. hatagirea* attaining the highest suitability when 'annual mean temperature' and 'annual precipitation' peaks at ca. 11.5 °C and 1,250 mm, respectively. The variables with greater influence (%) were annual precipitation (40.7), mean temperature of the wettest quarter (22.9), precipitation seasonality (16.6), and mean annual temperature (10.4). Under the current climate, about 790 km^2 that spread across Kashmir (274.1 km^2) Jammu (210.5 km^2), and Ladakh (305.6 km^2) were identified as high potential habitat (HPH) areas. The predicted distribution showed that for RCP 4.5 the HPH areas would decrease by 4.2 and 5.4%, by 2050 and 2070, while for RC P8.5 the decrease would be 18.1 and 8.7%, respectively. The shrinkage may be more obvious across tropical and temperate regions, while the species may gain new HPH areas across cold arid areas. Although HPH shrinkage for *D. hatagirea* appears mild, but as it exhibits high habitat specificity and grows inherently slow, this insignificant shrinkage may enhance its risk of local extinction. Therefore, an integrated approach involving *in-situ* measures across regions, where the species may disappear, and *ex-situ* measures, where it may expand, is hugely important.

Keywords

biodiversity, climate change, endangered plants, Himalaya, MaxEnt

Introduction

Among the most prominent challenges that endanger global biodiversity, climate change (Nunez et al., 2019), habitat loss (Marco et al., 2019) and overexploitation (Lughadha et al., 2020) rank high. These factors are viewed as major drivers that affect biological species from genes to ecosystems (Hoffmann et al., 2019), magnify the extinction crisis and exacerbate the challenge to conserve biodiversity (CBD, 2019). Among various eco-climatic regions, the future biodiversity scenario appears highly adverse across mountains, wherein these factors could seriously jeopardise species diversity, distribution, and services (Zlatanov et al., 2017; Peters et al., 2019). The species distribution scenarios built on a relationship between species and their biophysical environment form

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the critical component to conserve biodiversity in general and the services they provide, like in the case of medicinal plants (Singh et al., 2017). For narrow range species facing extinction threats, this is particularly important as it provides information regarding the suitability in their historical range and their reintroduction into more suitable habitats for their effective restoration. However, due to the variations in climate change projections from different models, a single model to identify such locations is considered superficial. Therefore, using an ensemble of forecasts from numerous climate models is highly preferred (Rathore et al., 2019).

Species distribution models (SDMs) are used widely for species distribution assessment under new environmental scenarios (Zhong et al., 2021). Among various applications, they are used for evaluating species invasion risks (Padalia et al., 2014), predicting the distribution of species facing extinction risks (Yi et al., 2014), and identifying suitable habitats for species reintroduction (Sharma et al., 2018). Among the various modelling techniques used in SDMs, which use species distribution and environmental data to predict species distribution, the Maximum Entropy (MaxEnt) is one of the most commonly used and is highly valuable for delineating species occurrence probability (Kaky et al., 2020). However, despite its ability to capture habitat suitability for species' distributions, the MaxEnt aids little in understanding the colonization (plant) under changing climate (Venne and Currie, 2021), and thus the use of a decision structured process for its evaluation is considered useful in determining its optimal model parameterization (Sorbe et al., 2023). Thus, when combined with ensemble projections from multiple GCMs, MaxEnt is highly preferred because it reduces the predictive uncertainty of single models (Knutti et al., 2017). Thus, using MaxEnt with multiple GCMs for mapping species distribution appears highly promising and helpful for conservation planning (Ayan et al., 2022).

With around one-third of terrestrial species, Orchidaceae is one of the most diverse families of flowering plants, with an estimated 25,000 species across 800 genera (Chug et al., 2009; Swarts and Dixon, 2009). Except for Antarctica, the orchids grow across all continents, with the highest diversity reported in tropical and subtropical regions (Pridegeon et al., 1999). In India, 1,331 species belonging to 186 genera of orchids have been reported (Natta et al., 2022), which grow across a broad altitudinal gradient from sea level to higher alpine regions. The orchids are habitat specialists and require unique micro-climatic conditions for growth and development (Jalal and Rawat, 2009). *Dactylorhiza* Necker ex Nevski (Orchidaceae) is a genus of about 75 species, distributed throughout the world but with higher dominance in Northern Hemisphere (Chauhan et al., 2014). *Dactylorhiza hatagirea* D. Don Soó, commonly known as Himalayan marsh orchid, is a perennial orchid found in the Himalayas in narrow pockets at altitudes between 2,500 and 5,000 m, mostly on open grassy slopes and alpine meadows (Fig. 1). Commonly known as "*Salam panja*" (Kashmir) and "*Wanglak* or *Angmo-lakpa*" (Ladakh), the plant is also used in modern medicine due to its aphrodisiac, immune modulator, expectorant, diuretic, astringent, nervine tonic, and hepato-protective properties (Warghat et al., 2013; Wani et al., 2021). A recent investigation estimated that the annual trade of *D. hatagirea* is around 10–50 metric tons (Goraya and Ved, 2017). However, the overexploitation of rhizomes and unlawful trading (Adhikari et al., 2008) has put severe pressure on the natural population of *D. hatagirea* across the Himalaya, to the point that the species is now identified as critically endangered (CAMP status), Endangered (IUCN status) and listed under Appendix II of Convention on International Trade in Endangered Species (CITES) (Thakur and Kaur, 2013; Dhiman et al., 2019).

Despite its medicinal and associated economic importance and extinction threat level, the earlier work across Jammu and Kashmir on orchids in general and *D. hatagirea*, in particular, have primarily focussed on their taxonomic enumeration, documentation and medicinal uses (Akhter et al., 2011; Warghat et al., 2012) and only recently have there been attempts to model its distribution (Wani et al., 2021). However, as the region might witness a temperature increase of 3.98 °C and 6.93 °C under RCP 4.5 and RCP 8.5 scenarios by the end of the 21st century (Romshoo et al., 2020), an approximation of distribution of *D. hatagirea* and where to restore its populations assumes key significance. Consequently, using an ensemble of four general circulation models (GCMs), the present study was conducted to map the current distribution of *D. hatagirea* across north-western Himalayas and predict its range shifts under future climate change scenarios. Specifically, the present study aims to understand a) the distributional pattern of *D. hatagirea* under current climate with an emphasis on different predictor variables, and b) quantify the magnitude of climate change impacts on its distribution for two representative concentration pathways (RCPs) ranging over next 50 years. The findings will aid to promote meaningful conservation strategies for the species and can guide its restoration across contrasting environments under climate change.

2. Materials and methods

Study area

North-western Himalayas consists of Jammu and Kashmir and Ladakh union territories (32º17' to 36º58'N and 73º26' to 80º30'E). The study area encompasses ecologically fragile ecosystems and is characterised by wide variations in altitude, edaphic contrasts, geological formations and different climatic zones. Jammu province comprises the outer ranges of Himalaya, Kashmir province comprises the inner ranges, and Ladakh province includes the Trans-Himalayan range. The climate ranges from tropical in Jammu province to temperate in Kashmir, while Ladakh experiences a cold arid climate. Owing to these variations, each region harbours a distinctive biodiversity pool and enjoys a unique position within the whole unified natural system. While the provinces of Jammu and Kashmir are well wooded and grow diverse forest types, the cold desert of Ladakh characterised by prolonged sub-zero temperatures and low annual precipitation is least wooded and grows sparsely distributed plant diversity.

Species data

Species occurrence data was obtained through a combination of methods involving detailed fieldwork, and compilation of species location points from Kashmir University Herbarium (KASH). We also used the data obtained from other secondary sources like Global Biodiversity Information Facility (GBIF) database (http://www.gbif.org), while its use as input in models of predicting species distributions is conditional and depends on the non-availability of other datasets, including the national databases (Štípková et al., 2024). However, a major source (>80%) of the occurrence data used for the present study involved our detailed field surveys carried across the region between 2010 and 2019 (Dad and Khan, 2011; Dad and Reshi, 2015; Dad, 2019) (Fig. 1). All these occurrence records were checked and subjected to further processing and screening using the SDM toolbox in ArcGIS 10.2.1. Particularly, we studied the spatial auto-correlation of species occurrence records and removed the redundant (duplicate and repeated) presences using average nearest neighbour analyses (Smeraldo et al., 2018). Thus out of the total 109 occurrence records for *D. hatagirea*, a spatial thinning along 5 × 5 km grid cells was performed to reduce model bias (Rana et al., 2020), and only 56 rarefied records were used to generate SDMs.

Environmental data

The environmental data was procured from the WorldClim database, version 1.4- http://www.worldclim.org/. Twenty predictor variables, including nineteen bioclimatic and one topographic (elevation) variable were downloaded at a spatial resolution of 30 arc-second (ca. 1 × 1 km, https://www.worldclim.org/data/worldclim21.html; https://www.worldclim.org/data/v1.4/cmip5.html). For each bioclimatic variable pair, Pearson's correlation coefficient was calculated using the ecological niche model (ENM) toolbox and variables that exhibited a high multicollinearity (>0.7) were eliminated from the analysis. Thus, the final seven predictor variables – annual mean temperature (°C; BIO1), mean diurnal range (max. temp–min. temp (°C; BIO2), temperature seasonality (SD × 100) (%; BIO4), mean temperature of the wettest quarter (°C; BIO8), annual precipitation (mm; BIO12), precipitation seasonality (coefficient of variation) (unitless; BIO15) and elevation (m) were selected and used for building habitat models. The same variables were used to project the habitat model under future global warming scenarios.

The projected changes of species distribution of *D. hatagirea* were modelled over the periods of 2050 (average for 2041–2060) and 2070 (average of 2061–2080) under two emission scenarios, including representative concentration pathways (RCPs) 4.5 and RCP8.5, which correspond to intermediate and high levels of global radiative forcing. We used four general circulation models, including GFDL-CM3 (Griffies et al., 2011), MRI CGCM3 (Yukimoto et al., 2012), CNRM CM5 (Voldoire et al., 2013) and CCSM4 (Al-Qaddi et al., 2017) for future climate change scenarios. The multi-model ensemble mean (MME) of four GCMs was calculated with equal weight

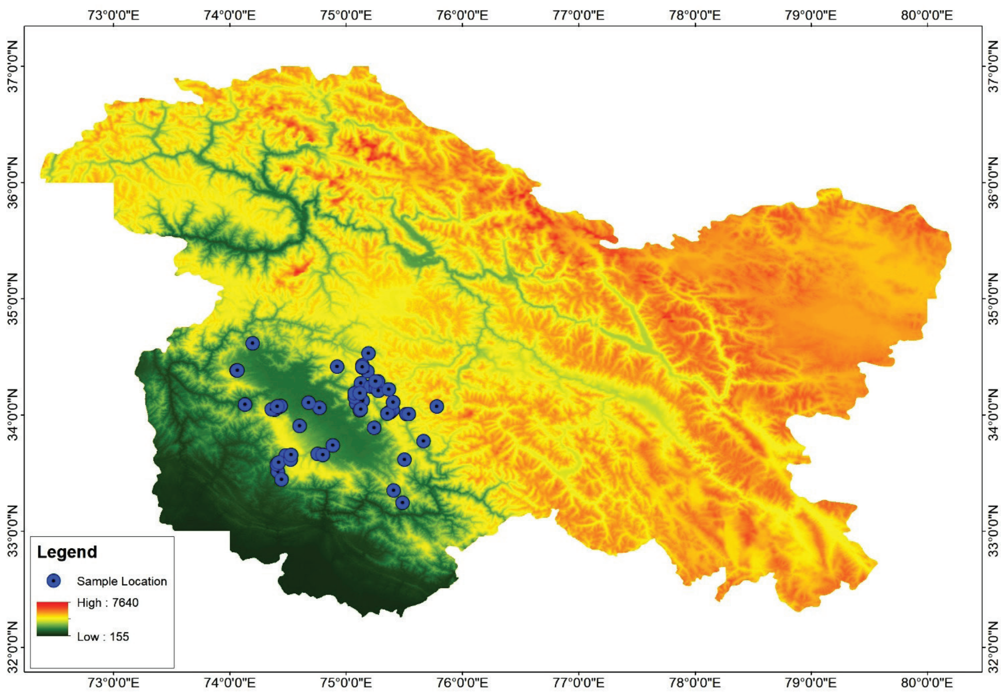

Fig. 1. Current distribution of *D. hatagirea*, shown as points, across North-Western Himalayas.

and used for building the model, used for studying the plant suitability and distribution under present scenario as well as used to project and predict the suitability in the future.

Model design

The model based on the seven predictor variables was run using the MaxEnt algorithm (version 3.4.1 k; Phillips et al., 2006) using background samples to represent natural conditions across the study area. The model calibration was carried using 75% data for training and 25% for testing. The average probability maps were obtained with ten replications. The model performance and accuracy were measured using the area under the curve (AUC) scores of receiver operator characteristic (ROC), TSS (True Skill Statistics), and Cohen's kappa (Fois et al., 2016). Amongst these, the ROC curve (AUC) represents the threshold-independent indices, while the TSS and Cohen's kappa are the threshold-dependent indices, with TSS dealing with both sensitivity and specificity. The value of TSS ranges from −1 to +1, where +1 indicates perfect agreement while scores from 0.6 to 0.9 specify fair to good model performance (Allouche et al., 2006). Different regularization parameters like mean regularized training gain, mean training area under the curve, and mean test area under the curve, that are a set of methods for reducing over-fitting, were recorded to check model over-fitting. The relative importance of each predictor was measured using the per cent contribution of the Jackknife test (Phillips et al., 2006). In this validation method, the models with AUC values of 0.5 and above are taken into consideration. For assessing the projected percentage change of suitable area in future scenarios, we used a distribution probability threshold of above 0.5 (Stockwell and Peterson, 2002). The habitat suitability map was converted into the suitable and unsuitable area (Xu et al., 2019). The potential suitable area was calculated using the Maximum Training Sensitivity Plus Specificity Logistic Threshold. The distribution map was then categorised into three main suitability classes, namely low, medium and high, with suitability values on a percentage basis being 25–50, 50–75 and >75%, respectively. The future distributions under two greenhouse gas (GHG) concentration trajectories (RCP 4.5 and RCP 8.5) of global circulation model GFDL-CM3, MRI CGCM3, CCSM4 and CNRM CM5 were carried using the same settings.

Habitat change assessment

The habitat change assessment for future climatic scenarios viz. 2050 (average for 2041–2060) and 2070 (average of 2061–2080) for RCP4.5 and RCP8.5 was computed following Weldemariam and Dejene (2021) and calculated as:

$$AC = \frac{Af - Ac}{Ac} \times 100,$$

where Af represents the area predicted as suitable habitat under 2050 and 2070 future climatic scenarios, while Ac represents the area predicted as suitable under current climate.

Results

Model evaluation

The model performance was high for both training and test data. As exemplified by AUC, TSS and other statistical scores like mean regularized training gain, mean training area under the curve, and mean test area under

Table 1. A statistical summary of average estimates of MaxEnt distribution models for *D. hatagirea* across North-Western Himalayas

Model	Climate scenario			Summary statistics							
				MR_{TG} (%)	MUR_{TG} (%)	M_{TG}	MT_{AUC}	Mt_{AUC}	$MAUC_{sd}$	Cohen's	TSS kappa
	Current			1.26	1.43	0.80	0.93	0.90	0.04	0.49	0.81
CCSM4	Future	2050	RCP4.5	0.88	1.00	0.90	0.94	0.92	0.05	0.46	0.77
	Projection		RCP8.5	1.10	1.09	0.80	0.91	0.89	0.06	0.44	0.79
		2070	RCP4.5	1.11	1.01	0.81	0.86	0.80	0.02	0.39	0.72
			RCP8.5	0.84	1.22	0.84	0.91	0.90	0.08	0.39	0.79
CNRM	Future	2050	RCP4.5	0.72	1.09	0.74	0.80	0.69	0.03	0.44	0.66
	Projection		RCP8.5	1.00	0.74	0.65	0.84	0.78	0.01	0.44	0.81
		2070	RCP4.5	1.01	1.21	0.78	0.76	0.74	0.12	0.46	0.73
			RCP8.5	0.66	0.99	0.88	0.80	0.79	0.13	0.48	0.71
MRI	Future	2050	RCP4.5	0.88	0.88	0.67	0.89	0.85	0.06	0.50	0.81
	Projection		RCP8.5	1.14	1.23	0.79	0.88	0.86	0.11	0.46	0.76
		2070	RCP4.5	1.02	1.22	0.77	0.83	0.81	0.13	0.49	0.77
			RCP8.5	0.80	0.88	0.81	0.89	0.84	0.04	0.49	0.80
GFDL	Future	2050	RCP4.5	0.80	1.11	0.87	0.94	0.90	0.02	0.44	0.69
	Projection		RCP8.5	1.04	1.19	0.80	0.86	0.82	0.04	0.46	0.70
		2070	RCP4.5	0.98	1.04	0.81	0.76	0.75	0.11	0.45	0.68
			RCP8.5	0.89	1.04	0.86	0.90	0.88	0.03	0.49	0.78

Abbreviations used include MR_{TG} – Mean regularized training gain (%); MUR_{TG} – Mean un-regularized test gain (%); M_{TG} – Mean test gain; MT_{AUC} – Mean training Area Under Curve; Mt_{AUC} – Mean test Area Under Curve and $MAUC_{sd}$ represents Mean Area Under Curve standard deviation and TSS represents true skill statistics.

Table 2. Estimates of average contribution and permutation importance of the environmental variables used in MaxEnt modelling of *D. hatagirea* across North-Western Himalayas

Variable	Percent contribution	Permutation importance
Bio8	19.16	22.91
Bio12	30.98	40.67
Bio15	11.05	16.56
Bio1	8.62	10.44
Bio4	21.37	3.93
Bio2	2.13	5.31
Elevation	6.66	0.68

the curve, the model performed satisfactorily across all four GCMs (Table 1), indicating that habitat suitability projections for *D. hatagirea* are fairly good.

Significant explanatory variables

D. hatagirea displayed highest sensitivity to precipitation, with annual precipitation (Bio 12) appearing particularly vital and contributing 40.7% to habitat suitability (Table 2). The mean temperature of the wettest quarter (Bio8) contributed 22.9%, while precipitation seasonality (Bio15) and mean annual temperature (Bio1) were other important variables (Table 2). The other predictor variables had little influence (Table 2). The results of the Jackknife test applied in this study further corroborated these results (Fig. 2).

Based on the results of relationship between predictor variables and probability of distribution typified by species response curves (Fig. 3), it is well evident that *D. hatagirea* attains the highest probabilities in environments when 'annual mean temperature' and 'annual precipitation' peaks at ca. 11.5 °C and 1,250 mm respectively, with decreasing probability thereafter. Similarly, it prefers precipitation seasonality (Bio15) of ca. 40 with a mean diurnal temperature (Bio2) range of ca. 12.5 °C (Fig. 3), and experiences a substantial decrease in distribution when mean temperature of wettest quarter (Bio8) increases. Topographically, the suitable habitat for *D. hatagirea* occurs in the high altitude range from ca. 2,500–4,000 m asl, with a peak at around 3,600 m asl (Fig. 3).

Current habitat suitability

The potential distribution of *D. hatagirea* across North-western Himalayas under the current climate using six bioclimatic variables and elevation is shown in Fig. 4. As is evident, the habitat suitability is highly inconsistent across the study area, with few specific areas appearing as its highest suitability habitats (HSHs). The HSHs spread across the high altitude ecosystems of Kashmir through the tropical habitats of Jammu to the lower reaches of Greater Himalayan montane system in Ladakh (Fig. 4). The species occurs in east of Kashmir towards the hilly regions, i.e. Kishtawar and Doda, while across the temperate region, its occupancy regions include the high altitude areas across Dachigam, Gurez, Pulwama, Anantnag, and Gulmarg, Pir ki Gali, Rupri, Nandansar across the Pir Panjal range under higher precipitation and colder temperature environments. The HSHs across Ladakh include Leh and Kargil, including Sankoo, Gundiyal, Dambur, Chutak, and Suktiyal, Sangrah, Purtikchey, and Bihmbhat. The results showed that HSHs (790.3 km^2) constitute about 0.78% of the study area (Table 3), with greater HSHs area (km^2) in Ladakh (305.6), followed by Kashmir (274.1), while the Jammu holds about 210.5 km^2 (Table 3).

Future potential distribution

D. hatagirea exhibited a mild reduction in the extent of HSHs for both RCP 4.5 and 8.5 for 2050 and 2070 (Fig. 5). The results showed that for RCP4.5, the HSHs for *D. hatagirea* would decrease by 4.2 and 5.4%, by 2050 and 2070, while for RCP8.5, and the projected decrease would be 18.1 and 8.7%, respectively (Table 4). However, the shrinkage in HSHs appeared more obvious across tropical (Jammu) and temperate (Kashmir) regions, while across the cold arid (Ladakh) region the species may gain new HSHs (Table 4). Such changes are evident from the predicted range and habitat change (%) of HSHs for *D. hatagirea* (Table 5). The results (Table 5) showed that between the two RCP scenarios, the high-end RCP 8.5 may be more severe across Kashmir, where it is projected to lose about 84.3 and 82.6% of its HSHs and Jammu, wherein the species is predicted to lose about 75.5 and 79.1% of its HSHs

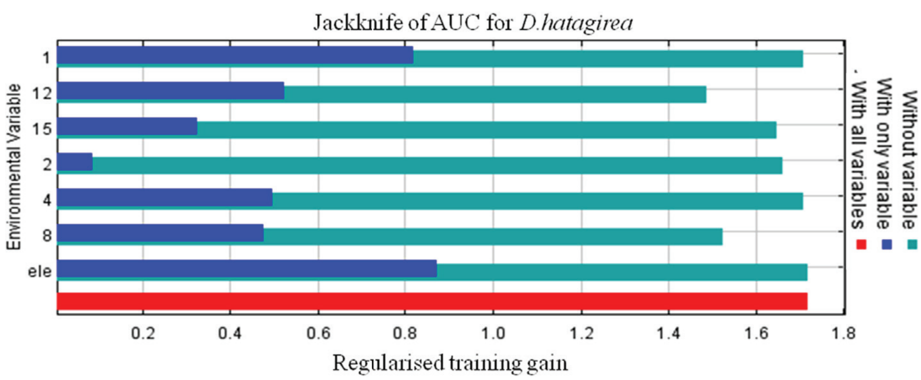

Fig. 2. Predictive accuracy of the model variables (Jackknife test) used in the ecological niche model for *D. hatagirea* across North-Western Himalayas.

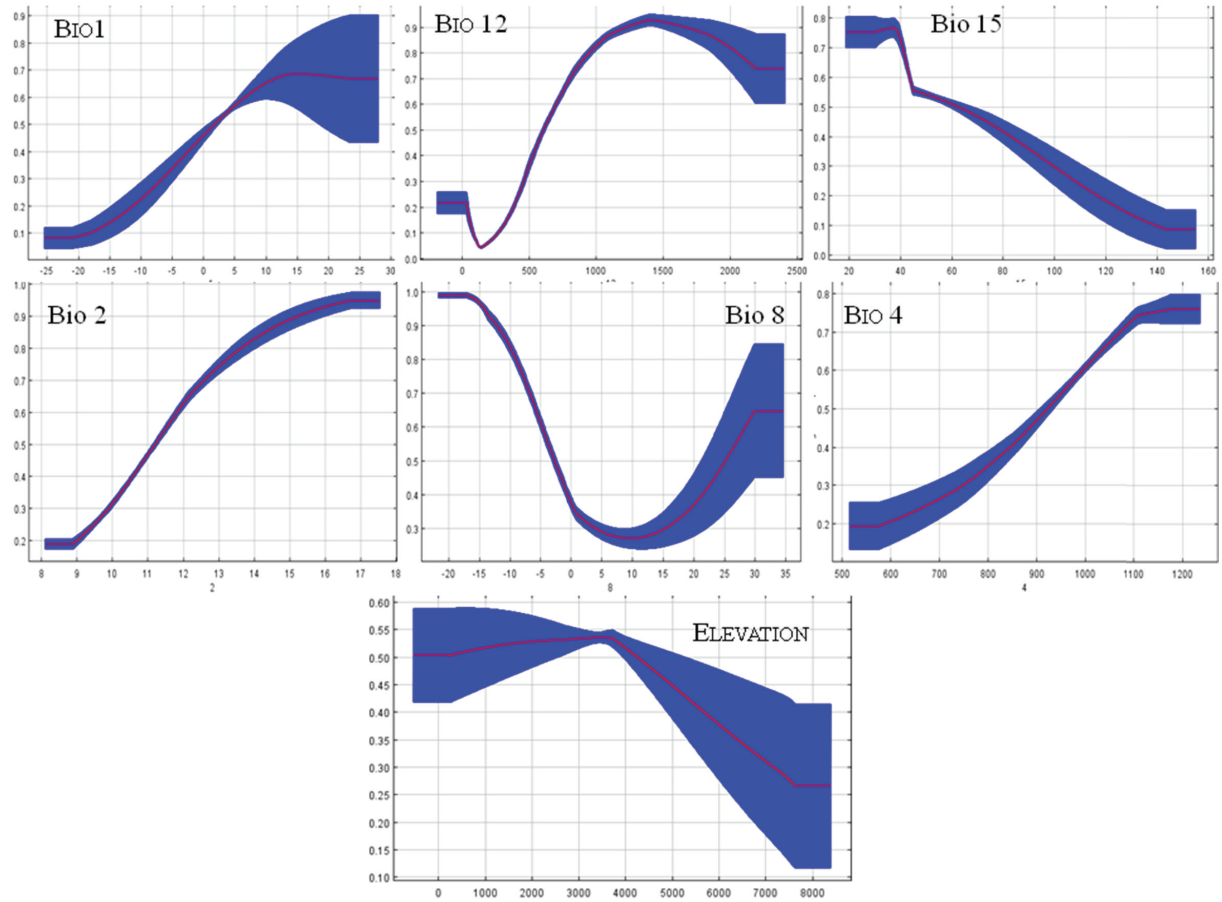

Fig. 3. Response curves of seven environmental predictors used in the ecological niche model for *D. hatagirea* across North-Western Himalayas. The y-axis of each response curve represents the probability of presence. For abbreviations, see Table 1.

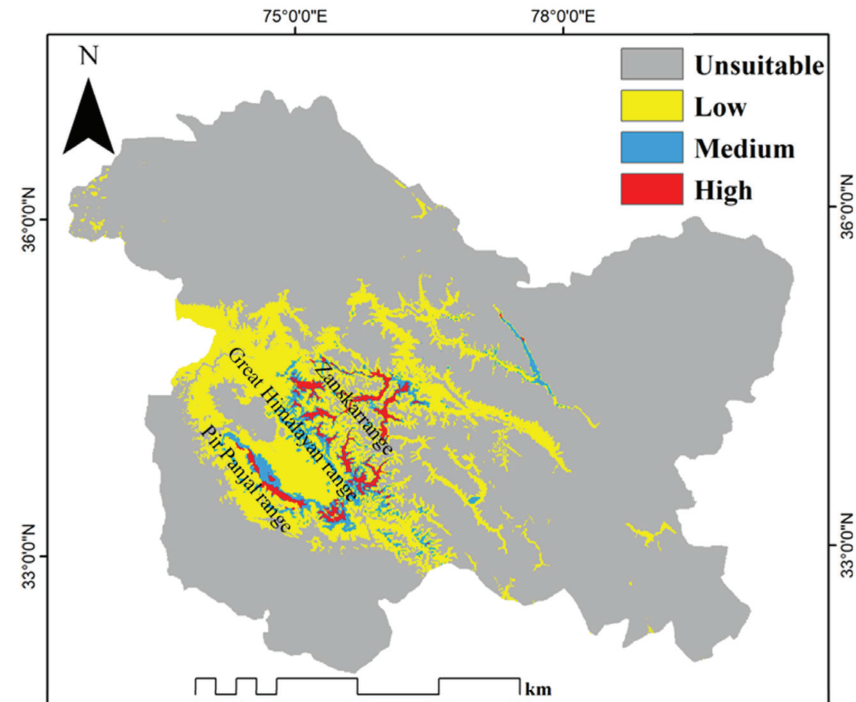

Fig. 4. Potential distribution range of *D. hatagirea* across North-Western Himalayas under current climate.

Table 3. Current habitat suitability (km²) for *D. hatagirea* across the North-Western Himalayas

Distribution class	Total area	Province		
		Jammu	Kashmir	Ladakh
Unsuitable	62,361.9 (61.5)	18,098.5 (68.8)	3,463.6 (21.7)	40,799.8 (68.9)
Low potential	32,046.5 (31.6)	5,905.9 (22.4)	9,305.3 (58.4)	16,835.4 (28.4)
Moderate potential	6,188.9 (6.1)	2,078.2 (7.9)	2,905.4 (18.2)	1,205.3 (2.1)
High potential	790.3 (0.78)	210.5 (0.8)	274.1 (1.7)	305.6 (0.5)

The area has been calculated for three provinces of Indian administered Jammu, Kashmir and Ladakh.

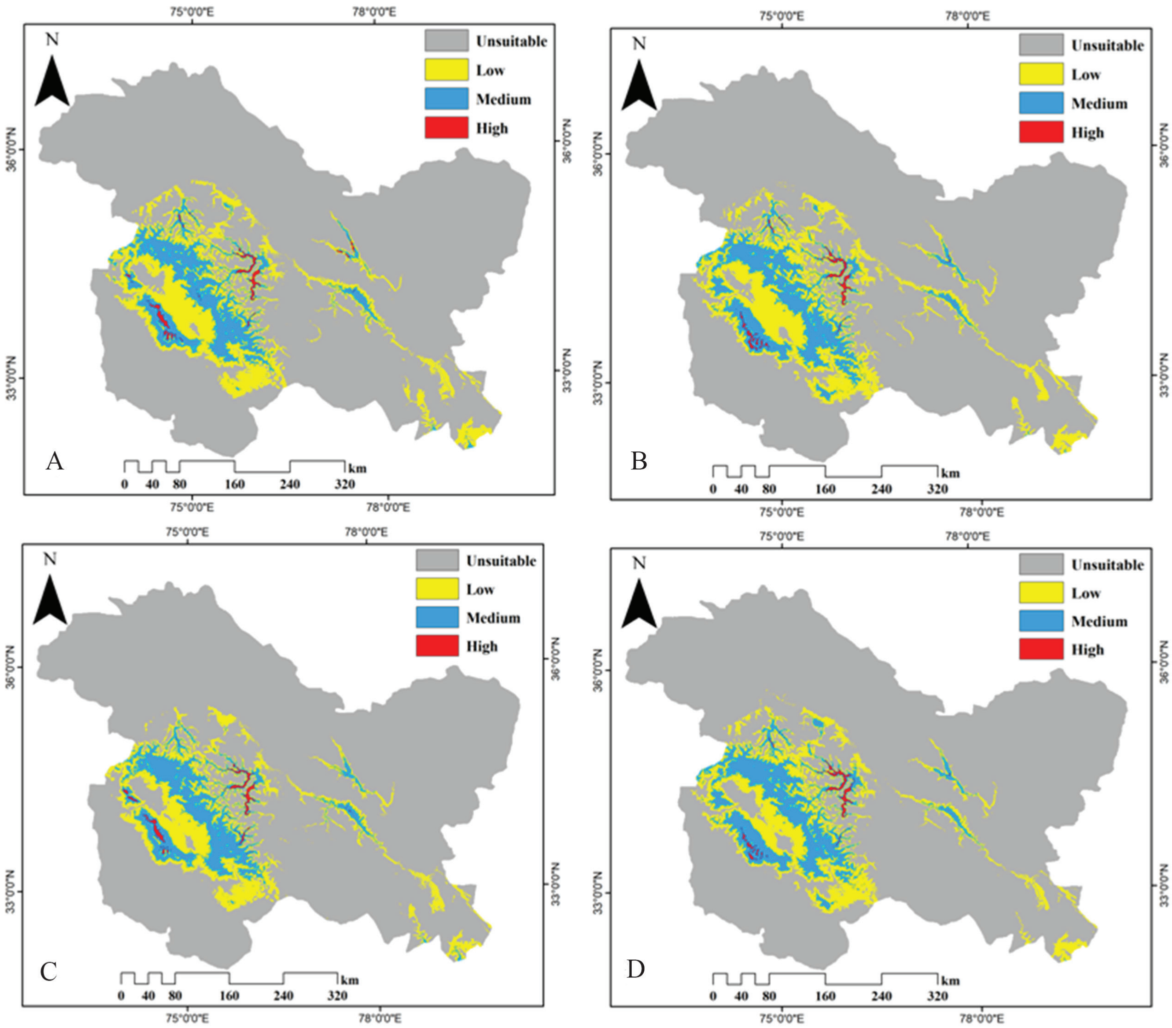

Table 4. Predicted range changes (km2) of high potential areas for *D. hatagirea* under future climate change scenarios at RCP 4.5 and RCP 8.5 for 2050 and 2070 across North-Western Kashmir Himalaya

Distribution class	Future scenarios			
	2050		2070	
	RCP4.5	RCP8.5	RCP4.5	RCP8.5
	Area (km²)	Area (km²)	Area (km²)	Area (km²)
Unsuitable	55,638.6	53,728.8	56,631.9	53 890.5
Low potential	29,844.6	30,819.2	29,226.5	30 416.3
Moderate potential	15,146.76	16,191.9	14,781.7	16 359.7
High potential	757.6	647.6	746.9	853.1

Suitability level percentage (%) of Jammu and Kashmir's area is calculated for 101,387 km², i.e. three provinces of Indian administered Jammu, Kashmir and Ladakh.

Table 5. Predicted range (km^2) and habitat change (%) of high potential areas for *D. hatagirea* under current and future climate change scenarios at RCP4.5 and RCP8.5 for 2050 and 2070 across three provinces across North-Western Kashmir

Region	Current area	Future climate scenario			
		2050		2070	
		RCP4.5	RCP8.5	RCP4.5	RCP8.5
Ladakh	305.6	414.08 (+33.2)	553.14 (+81.0)	440.35 (+23.8)	636.65 (+106.1)
Kashmir	274.1	264.41 (–3.5)	42.90 (–84.3)	254.33 (7.7)	40.53 (–82.6)
Jammu	210.5	79.20 (–67.1)	51.62 (–75.5)	51.71 (–64.9)	43.90 (–79.1)

Distribution across only high potential areas, i.e. habitat suitability >75% are shown. The values in parenthesis represent the habitat change on % basis, with (+) sign indicating an increase and (–) sign depicting the decrease.

for future climate scenario of 2050 and 2070, respectively. However, for the Ladakh, the species may gain HSHs of about 81.0 and 106.1% in both near (2050s) and distant (2070s) future scenarios (Table 5).

Discussion

The high AUC values for *D. hatagirea* in the present study (Table 1) concord with earlier observations that species with restricted ranges display higher AUC values (Yang et al., 2013). The other model performance indices viz. TSS and Cohen's kappa as well as detailed summary statistics like mean regularized training and test gain (%), mean test gain, and mean test AUC indicated that *D. hatagirea* predictions across the study area are fairly good (Fig. 2). Indeed in line with field-based data and earlier reports (Shapoo et al., 2014), the climatic niche of *D. hatagirea* across Northwestern Himalayas mainly occurs in sub-alpine and alpine altitudes (Fig. 3). Despite reports that model predictions may overrate actual species distributions (Warren and Seifert, 2011), studying the *D. hatagirea* distribution across North-western Himalayas, which lacks vital ecological data about highly threatened species, holds immense value and offers broader scope for conservation and management.

Under the current climate, the predictor variable importance (Table 2) pointed to the higher influence (%) of annual precipitation (40.7), mean temperature of the wettest quarter (22.9), precipitation seasonality (16.6) and mean annual temperature (10.4). The differences in the predictive environmental variables important for the distribution of *D. hatagirea* have been reported by various authors. For example, Thakur et al. (2021) reported the precipitation of coldest quarter, mean temperature of driest quarter, annual mean temperature and mean diurnal range as most important variables that determine the distribution of *D. hatagirea* across the Himalaya while Wani et al. (2022), using various algorithms, including MaxEnt, reported mean temperature of wettest quarter, and annual mean temperature as important variables that govern the species potential distribution across the Himalaya. The results of the present study are in disagreement with WANI et al. (2021), who observed minor differences amongst predictive variables for *D. hatagirea* distribution across North-western Himalayas. This incongruity presumably stems from the inclusion of too many environmental variables (n = 11) by Wani et al. (2021), as compared to the present study, wherein only non-collinear (n = 7) variables were used. These variables provide desired information about main ecological requirements about *D. hatagirea* and thus helps understand its performance under different regimes of habitat conditions.

The results showed that both precipitation and temperature are important to the sustenance of *D. hatagirea* across North-western Himalayas. Throughout its distributional range, *D. hatagirea* is usually common at altitudes above 3,000 m asl, wherein it mainly occupies gentle slopes, open grassy slopes, meadows along streams and alpine meadows under higher precipitation and colder temperature regimes (Dad and Khan, 2011). Studies outside North-Western Himalaya (Singh et al., 2021; Thakur et al., 2021) have also reported its higher occurrence on areas with high moisture content than bare rocky slopes or crevices and attributed it to the mosaic of habitat types and influence of abiotic/edaphic factors (Noroozi et al., 2015). Except for cold arid Ladakh, Jammu and Kashmir receive sufficient amounts of rainfall during winter months which lasts long as snow, adds to soil moisture and contributes to its growth and development. The species response curves (Fig. 3) indicating that *D. hatagirea* attains highest suitability in environments when 'annual mean temperature' and 'annual precipitation' peaks at ca. 12.5 °C and 1,250 mm, respectively, with decreasing probability thereafter further support our observations. As for altitude, the highest probability of occurrence is at altitudes between 2,500–4,000 m asl, with peak at ca. 3,600 m asl (Fig. 3). Notwithstanding the sporadic observations documenting *D. hatagirea* at higher altitudes ca. 4,150 m asl (Shaheen et al., 2019), it is widely held that sub-alpine and alpine zones between 2,800 m and 4,200 m asl are most suitable for *D. hatagirea* (IUCN, 2004). The present study identified ca. 62,361.9, 32,046.5, 6,188.9 and 790.3 km^2 as unsuitable, low, medium and high suitability areas for *D. hatagirea* and, therefore, suggests that the approximations reported by Wani et al. (2021) of 25, 108, 316, and 167 km^2 as least suitable, marginally suitable, moderately suitable and highly suitable for *D. hatagirea* across Jammu and Kashmir are rather gross underestimates.

Furthermore, the response curves also showed as to how the precipitation and temperature dependant variables affect *D. hatagirea* distribution, as its probability of occurrence approaches maximum when annual precipitation is >1,000 mm a^{-1}, medium precipitation seasonality is ca. 40%, mean temperature of the wettest quarter is ca. –20 °C, and temperature seasonality is ca. 1,100%, while the probabilities decrease steadily after that (Fig. 3). Similar observations have been recorded elsewhere for other high alpine species (Rana et al., 2017), indicating that *D. hatagirea* ideally prefers harsh winters with good precipitation. This goes well with its habit because as *D. hatagirea* is perennial with underground rhizomes, it prefers cold temperatures. The results further showed that despite an increase above 12.5 °C for mean annual temperature, the probability occurrence changes little. Since temperatures are projected to increase greatly in this area, this finding holds substantial conservation implications for *D. hatagirea* across North-western Himalayas.

Plant responses to climate change are highly variable (Gebrewahid et al., 2020), with broad range species predicted to adapt better than narrow range species (Abolmaali et al., 2018). For *D. hatagirea* across North-western Himalayas, the present study indicated that its HSHs would decrease (%) by 4.2 & 5.4, and by 18.1 & 8.7, under RCP 4.5 and 8.5 for future climate scenario of 2050 and 2070 respectively (Table 4). This appears quite lower than what has been reported for it across various other Himalayan regions. For example, for Nepal Himalaya, using four climate change models and two greenhouse gas concentration trajectories of 4.5 and 8.5, Shrestha et al. (2021) reported losses 71–81% by 2050 and 95–98% by 2070 for suitable habitats of *D. hatagirea*. However, despite a mild decrease reported in the present study, as *D. hatagirea* is highly habitat specific (Agarwal et al., 2008), grows slowly (Vij, 2002), requires mycorrhizal association (Warghat et al., 2013), needs finest environment to overcome physiological barriers (Baskin and Baskin, 1998), and constitutes a preferred food of Himalayan monal (*Lophophorus impejanus*) and Pika (*Ochotona roylei*) (Dhyani and Kala, 2005), the shrinkage will likely trigger multiple conservation challenges. Furthermore, its comparably lower density in this region (1.16 individual m^{-2} – Dad and Khan, 2011) than across other Himalayan regions like Uttrakhand and Himachal (1.89–2.19 individual m^{-2}, Bhatt et al., 2005; 2.66–3.2 individual m^{-2}, Nautiyal et al., 2004), may put it at greater risk. The near absence of cultivation practices, production technology and propagation protocol development and ever-increasing anthropogenic pressures may further worsen the situation and increase its potential risk of local extinction.

The predicted change in HSHs exhibited highest shrinkage across tropical and temperate areas and an increase across cold arid regions (Fig. 6). Studies conducted

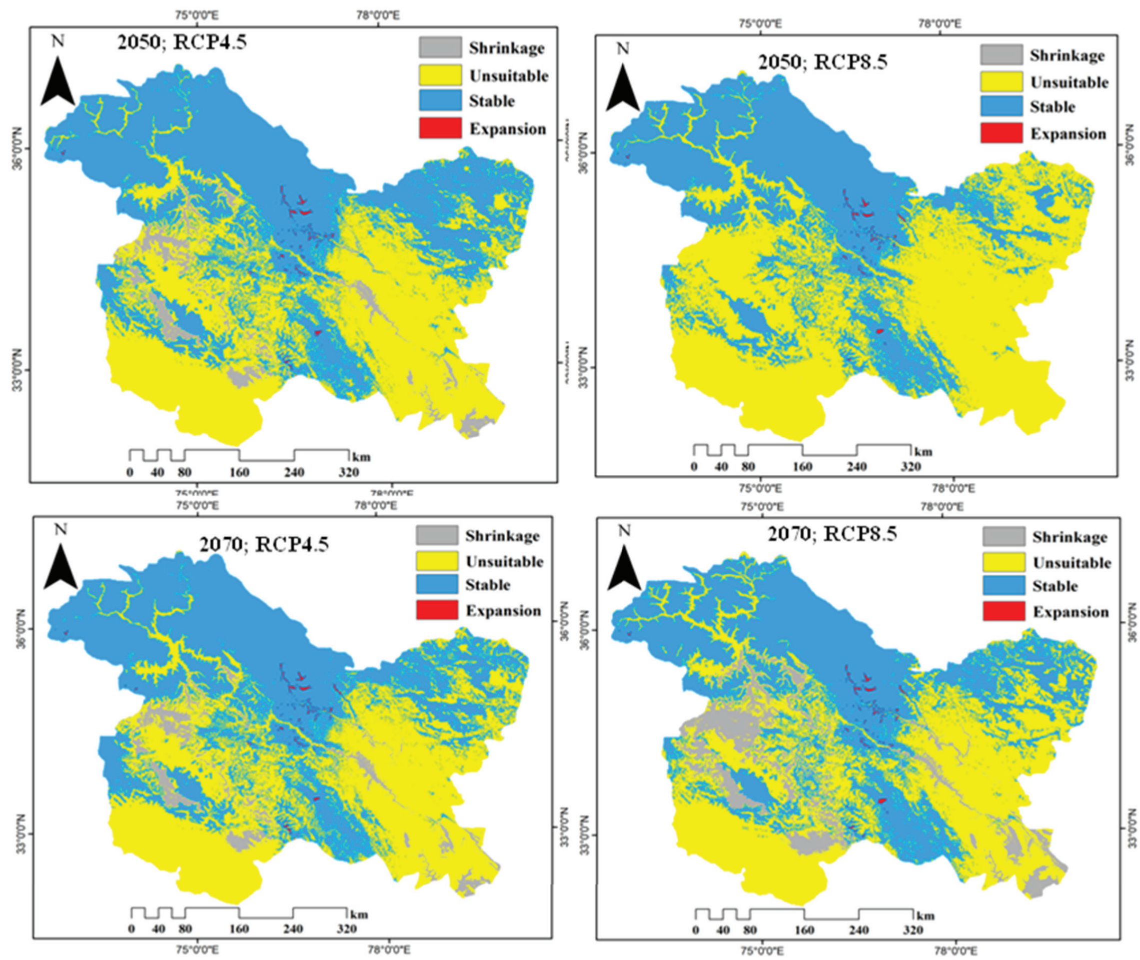

Fig. 6. Maps of potentially stable, expansion, and shrinkage areas for *D. hatagirea* under future climate scenario for the RCP 4.5 and RCP 8.5 for the year 2050 and 2070 across North-Western Himalayas.

elsewhere by Parolo and Rossi (2008) and Matteodo et al. (2013) also observed that changing climate pushes plants towards higher elevations and latitudes, while for *D. hatagirea* Singh et al. (2022) also recorded northward expansion in HSHs under both RCP 4.5 and RCP 8.5, with an expansion of around 11–22% for the year 2050. In the present study, this expansion shows that the changing climate may impact species differently. This differing impact could be the function of varying climate regimes across different regions and highlights the importance of spatial scale in distribution modelling and conservation planning. Nonetheless, the expansion across cold arid areas should be described cautiously due to the absence of biotic interactions and species characteristics like dispersal, that hugely influence species distributions (Wisz et al., 2013) in our distribution modelling.

The results of our habitat change assessment showed that RCP 8.5 may be more severe for *D. hatagirea* across Kashmir and Jammu while across cold arid Ladakh the species may gain new HSHs (Table 5). Thus RCP 8.5 represents both the lower and higher distribution end for *D. hatagirea*. As RCP 8.5 implies an increase of 2.0 and 3.7 °C above the pre-industrial level in the year 2050 and 2070, respectively (IPCC, 2014), the results connote that while across temperate and tropical areas, *D. hatagirea* would fail to withstand increasing temperatures, it will fairly flourish across the cold arid region (Fig. 6). *For Taxus wallichiana*, Rathore et al. (2019) also reported RCP 8.5 as favourable in expanding its habitat range across Himalaya. However, given the switch of HSHs, particularly at high altitude ecosystems across Kashmir Himalaya, which are currently highly suitable and will experience decreasing suitability (Fig. 5), these areas should be protected and utilised as *in situ* conservation areas. Most plants with medicinal importance in this region have small populations with high habitat preferences, making them prone to unregulated exploitation and endangerment (Dad, 2019). Similarly, the areas across the Pir Panjal mountain range, wherein the species may experience minor changes, and across the Zanskar range, where it may find suitable habitats in both near and distant future scenarios (Fig. 5), could be utilised for *ex-situ conservation* measures like reintroduction and cultivation etc. Given that plant conservation through reserves may not keep pace with extinction rates triggered by habitat loss and global climate change (Swarts and Dixon, 2009), this integrated approach is hugely important. In this direction, the present study offers a valuable database and direction in determining HPHs for undertaking conservation decisions which will be helpful for *D. hatagirea* as well as other threatened plant species. It is equally important to monitor and check the contemporary conservation challenges like grazing, overexploitation and illegal trade, unsustainable harvesting practices like premature plant collection, and promote its cultivation across the region with due emphasis on its propagation protocol.

Conclusions

The geographical distribution of *Dactylorhiza hatagirea* over north-western Himalayas was modelled using four general circulation models. The results showed that annual precipitation and mean temperature of the wettest quarter are hugely important for its current distribution. The multi-model ensemble mean revealed that representative concentration pathway (RCP) 8.5 would severely impact *D. hatagirea*. The habitat change assessment exhibited severe shrinkage across temperate and sub-tropical regions, while a northward expansion towards cold arid areas was noticeable. This differing response across contrasting environments under climate change has vital implications for conservation planning across the Himalaya.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Availability of data and material

The data is available upon request to the authors.

References

Abolmaali, R., Tarkesh, M., Bashari, H., 2018. MaxEnt modeling for predicting suitable habitats and identifying the effects of climate change on a threatened species, Daphne mucronata, in central Iran. *Ecological Informatics*, 43: 116–123. https://doi.org/10.1016/j.ecoinf.2017.10.002

Adhikari, D., Reshi, Z., Datta, B.K., Samant, S.S., Chettri, A., Upadhaya, K., Shah, M.A., Singh, P.P., Tiwary, T., Majumdar, K., Pradhan, A., Thakur, M.L., Salam, N., Zahoor, Z., Agarwal., A., Khokhar, D., Vishwanath, 2008. Conservation through in vitro propagation of a critically endangered medicinal plant, Dactylorhiza hatagirea (D. Don) Soó. In Reddy, M.V. (eds). *Wildlife biodiversity conservation*. Daya Publishing House, p. 294–299.

Akhter, C., Khuroo, A.A., Dar, G.H., Khan, Z.S., Malik, A.H., 2011. An updated checklist of orchids in the Indian Himalayan State of Jammu and Kashmir. *Pleione*, 5 (1): 1–9.

Allouche, O., Tsoar, A., Kadmon, R., 2006. Assessing the accuracy of species distribution models: prevalence, kappa and the true skill statistic (TSS). *Journal of Ap-*

plied Ecology, 43 (6): 1223–1232. https://doi.org/10.1111/j.1365-2664.2006.01214.x Al-Qaddi, N., Vessella, F., Stephan, J., Al-Eisawi, D., Schirone, B., 2017. Current and future suitability areas of kermes oak (Quercus coccifera L.) in the Levant under climate change. *Regional Environment Change*, 17: 143–156. https://doi.org/10.1007/s10113-016-0987-2

Ayan, S., Bugday, E., Varol T., Ozel, B.H., Thurm, E.A., 2022. Effect of climate change on potential distribution of oriental beech (Fagus orientalis Lipsky.) in the twenty frst century in Turkey. *Theoretical and Applied Climatology*, 148: 165–177. https://doi.org/10.1007/s00704-022-03940-w

Baskin, C.C., Baskin, J.M., 1998. *Seeds: ecology, biogeography, and, evolution of dormancy and germination*. San Diego: Academic Press. 666 p.

Bhatt, A., Joishi, S.K., Garola, S., 2005. Dactylorhiza hatagirea (D. Don) Soó - a west Himalayan orchid in Peril. *Current Science*, 89: 610–612. https://www.jstor.org/stable/24111155

CBD, 2019. *Biodiversity and the 2030 Agenda for sustainable development*. Technical note. Montréal, Quebec, Canada: Secretariat of the Convention on Biological Diversity. [cit. 2024-07-22]. https:/www.cbd.int/development/doc/biodiversity-2030-agenda-technical-note-en.pdf.

Chauhan, R.S., Nautiyal, M.C., Vashistha, R.K., Prasad, P., 2014. Morpho-biochemical variability and selection strategies for the germplasm of Dactylorhiza hatagirea (D. Don) Soó: an endangered medicinal orchid. *Journal of Botany,* 2014: article ID 869167, 5 p. https://doi.org/10.1155/2014/869167

Chugh, S., Guha, S., Rao, I.U., 2009. Micropropagation of orchids: a review on the potential of different explants. *Scientia Horticulture*, 122: 507–507. https://doi.org/10.1016/j.scienta.2009.07.016

Dad, J., 2019. Phytodiversity and medicinal plant distribution in pasturelands of North Western Himalaya in relation to environmental gradients. *Journal of Mountain Science,* 16 (4): 884–897. https://doi.org/10.1007/s11629-018-5104-1

Dad, J.M., Khan, A.B., 2011. Threatened medicinal plants of Gurez valley, Kashmir Himalayas: distribution pattern and current conservation status. *International Journal of Biodiversity Science, Ecosystem Services and Management*, 7 (1): 20–26.

Dhiman, N., Sharma, N.K., Thapa, P., Sharma, I., Swarnkar, M.K., Chawla, A., Shankar, R., Bhattacharya, A., 2019. De novo transcriptome provides insights into the growth behavior and resveratrol and trans-stilbenes biosynthesis in Dactylorhiza hatagirea - an endangered alpine terrestrial orchid of western Himalaya. *Scientific Reports*, 9: 13133. https://doi.org/10.1038/s41598-019-49446-w

Dhyani, P.P., Kala, C.P., 2005. Current research on medicinal plants: five lesser-known but valuable aspects. *Current Science*, 88 (3): 335

Fois, M., Cuena-Lombraña, A., Fenu, G., Cogoni, D., Bacchetta, G., 2016. The reliability of conservation status assessments at regional level: past, present and future perspectives on Gentiana lutea L. ssp. lutea in Sardinia. *Journal of Nature Conservation*, 33: 1–9. https://doi.org/10.1016/j.jnc.2016.06.001

Gebrewahid, Y., Abrehe, S., Meresa, E., 2020. Current and future predicting potential areas of Oxytenanthera abyssinica (A. Richard) using MaxEnt model under climate change in Northern Ethiopia. *Ecological Processes*, 9: article number 6 (2020). https://doi.org/10.1186/s13717-019-0210-8

Goraya, G.S., Ved, D.K., 2017. *Medicinal plants in India: an assessment of their demand and supply*. New Delhi: National Medicinal Plants Board, Ministry of AYUSH, Government of India; Dehradun: Indian Council of Forestry Research and Education. 395 p.

Griffies, S., Winton, M., Donner, L., Horowitz, L., Downes, S., Farneti, R., Gnanadesikan, A., Hurlin, W., Lee H., Liang, Z., Palter, J., 2011. The GFDL CM3 coupled climate model: characteristics of the ocean and sea ice simulations. *Journal of Climatology*, 24 (13): 3520–3544. https://doi.org/10.1175/2011JCLI3964.1

Hoffmann, A.A., Rymer, P.D., Byrne, M., Ruthrof, K.X., Whinam, J., McGeoch, M., Bergstrom, D.M., Guerin, G.R., Sparrow, B., Joseph, L., Hill, S.J., Andrew, N.R., Camac, J., Bell, N., Riegler, M., Gardner, J.L., Williams, S.E., 2019. Impacts of recent climate change on terrestrial flora and fauna: some emerging Australian examples. *Australian Ecology*, 44: 3–27. https://doi.org/10.1111/aec.12674

IPCC, 2014. *Climate Change 2014. Synthesis report. Contribution of working groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Core Writing Team, Pachauri, R.K., Meyer, L.A(eds)]. IPCC, Switzerland. 151 p.

IUCN. 2004. *National register of medicinal and aromatic plants*. International Union for Nature Conservation Nepal, Kathmandu, Nepal.

Jalal, J.S., Rawat, G.S., 2009. Habitat studies for conservation of medicinal orchids of Uttarakhand, Western Himalaya. *African Journal of Plant Science*, 3 (9): 200–204.

Kaky, M., Nolan, V., Alatawi, A., Gilbert, F., 2020. A comparison between Ensemble and MaxEnt species distribution modelling approaches for conservation: a case study with Egyptian medicinal plants. *Ecological Informatics*, 60: 101150. https://doi.org/10.1016/j.ecoinf.2020.101150

Lughadha, E. N., Bachman, S.P., Leão, T.C.C., Forest, F., Halley, J.M., Moat, J., Acedo, C., Bacon, K.L., Brewer, R.F.A., Gâteblé, G., Gonçalves, S.C., Govaerts, R., Hollingsworth, P.M., Krisai-Greilhuber, I., de Lirio, E.J., Moore, P.G.P., Negrão, R., Onana, J.M., Rajaovelona, L.R., Razanajatovo, H., Reich, P.B., Richards, S.L., Rivers, M.C., Cooper, A., Iganci, J., Lewis, G.P., Smidt, E.C., Antonelli, A., Mueller, G.M., Walker, B.E., 2020. Extinction risk and threats to plants and fungi. *Plants People Planet*, 2: 389–408. https://doi.org/10.1002/ppp3.10146

Marco, M.D., Harwood, T.D., Hoskins, A.J., Ware, C., Hill, S.L.L., Ferrier, S., 2019. Projecting impacts of global climate and land-use scenarios on plant biodiversity using compositional-turnover modelling. *Global Change Biology*, 25 (8): 2763–2778. https://doi.org/10.1111/gcb.14663

Matteodo, M., Wipf, S., Stöckli, V., Rixen, C., Vittoz, P., 2013. Elevation gradient of successful plant traits for colonizing alpine summits under climate change. *Environment Research Letters*, 8 (2): 024043. https://doi.org/10.1088/1748-9326/8/2/024043

Natta, S., Mondal, S.A., Pal, K., Mandal, S., Sahana, N., Pal, R., Pandit, G.K., Alam, B. K., Das, S.S., Biswas, S.S., Kalaivanan, N.S., 2022. Chemical composition, antioxidant activity and bioactive constituents of six native endangered medicinal orchid species from north-eastern Himalayan region of India. *South African Journal of Botany*, 150: 248–259. https://doi.org/10.1016/j.sajb.2022.07.020

Nautiyal, M.C., Nautiyal, B.P., Prakash, V., 2004. Effect of grazing and climatic changes on alpine vegetation of Tungnath, Garhwal Himalaya, India. *Environmentalist*, 24: 125–134. https://doi.org/10.1007/s10669-004-4803-z

Noroozi, J., Moser, D., Essl, F., 2015. Diversity, distribution, ecology and description rates of alpine endemic plant species from Iranian mountains. *Alpine Botany*, 126 (1): 1–9. https://doi.org/10.1007/s00035-015- 0160-4

Nunez, S., Arets, E., Alkemade, R., Verwer, C., Leemans, R., 2019. Assessing the impacts of climate change on biodiversity: is below 2 °C enough? *Climatic Change*, 154: 351–365. https://doi.org/10.1007/s10584-019-02420-x

Padalia, H., Srivastava, V., Kushwaha, S.P.S., 2014. Modeling potential invasion range of alien invasive species, Hyptis suaveolens (L.) Poit. in India: comparison of MaxEnt and GARP. *Ecological Informatics*, 22: 36–43. http://dx.doi.org/10.1016/j.ecoinf.2014.04.002

Parolo, G., Rossi, G., 2008. Upward migration of vascular plants following a climate warming trend in the Alps. Basic *Applied Ecology,* 9: 100–107. https://doi.org/10.1016/j.baae.2007.01.005

Peters, M.K., Hemp, A., Appelhans, T., Becker., J.N., Behler, C., Classen, A., Detsch, F., Ensslin, A., Ferger, S.W., Frederiksen, S.B., Gebert, F., Gerschlauer, F., Gütlein, A., Helbig, M., Hemp, C., Kindeketa, W.J., Kuhnel, A., Mayr, A.V., Mwangomo, E., Ngereza, C., Njoyu, H.K., Otte, I., Pabst, H., Renner, M., Roder, J., Rutten, G., Costa, D.S., Sierra-Cornejo, N., Vollstadt, M.G.R., Dulle, H.I., Eardley, C.D., Howell, K.M., Keller, A., PETERS, R.S., Ssymank, A., Kakengi, V., Zhang, J., Bogner, C., Bohning-Gaese, K., Brandl, P., Hertel, D., Huwe, B., Kiese, R., Kleyer, M., Kuzyakov, Y., Nauss, T., Schleuning, M., Tschapka, M., Fischer, M., Steffen-Dewenter, I., 2019. Climate–land-use interactions shape tropical mountain biodiversity and ecosystem functions. *Nature*, 568: 88–92. https://doi.org/10.1038/s41586-019-1048-z

Phillips, S., Anderson, R., Schapire, R., 2006. Maximum entropy modelling of species geographic distributions. *Ecological Modelling*, 190: 231–259. https://doi.org/10.1016/j.ecolmodel.2005.03.026

Pridgeon, A, Chase, M., Cribb, P., Rasmussen, F.N., 1999. *Genera Orchidacearum. Vol. 1.* Oxford, U.S.A: Oxford University Press. 230 p.

Rana, H.K., Luo, D., Rana, S.K., Sun, H., 2020. Geological and climatic factors affect the population genetic connectivity in Mirabilis himalaica (Nyctaginaceae): insight from phylogeography and dispersal corridors in the Himalaya-Hengduan Biodiversity Hotspot. *Frontiers in Plant Science*, 10: 1721. https://doi.org/10.3389/fpls.2019.01721

Rana, S., Rana, H., Ghimire, S., 2017. Predicting the impact of climate change on the distribution of two threatened Himalayan medicinal plants of Liliaceae in Nepal. *Journal of Mountain Science*, 14 (3): 558–570. https://doi.org/10.1007/s11629-015-3822-1

Rathore, P., Roy, A., Karnatak, H., 2019. Modelling the vulnerability of Taxus wallichiana to climate change s cenarios in South East Asia. *Ecological Indicators*, 102: 199–207. https://doi.org/10.1016/j.ecolind.2019.02.020

Romshoo, S.A., Bashir, J., Rashid, I., 2020. Twenty-first century-end climate scenario of Jammu and Kashmir Himalaya, India, using ensemble climate models. *Climate Change*, 162 (3): 1473–1491. https://doi.org/10.1007/s10584-020-02787-2

Shaheen, H., Ibrahim, M., Ullah, Z., 2019. Spatial patterns and diversity of the alpine flora of Deosai plateau, Western Himalayas. *Pakistan Journal of Botany*, 51 (1): 205–212. http://dx.doi.org/10.30848/PJB2019-1(39)

Shapoo, G.A., Kalo, Z.A., Singh, S., Ganie, A.H., Padder, B.M., 2014. Evaluation of diversity and habitat types of some orchid species growing in Kashmir Himalaya. *Species*, 10 (22): 8–13.

Sharma, S., Arunachalam, K., Bhavsar, D., Kala, R., 2018. Modelling habitat suitability of Perilla frutescens with MaxEnt in Uttarakhand—A conservation approach. *Journal of Applied Research in Medicinal and Aromatic Plants*, 10: 99–105. https://doi.org/10.1016/j.jarmap.2018.02.003

Shrestha, B., Tsiftsis, S., Chapagain, D.J., Khadka, C., Bhattarai, P., Kayastha, Shrestha, N., Alicja, Kolanowska, M., Kindlmann, P., 2021 Suitability of habitats in Nepal for Dactylorhiza hatagirea now and under predicted future changes in climate. *Plants*, 10 (3): 467. https://doi.org/10.3390/plants10030467

Singh, L., Kanwar, N., Bhatt, I.D., Nandi, S.K., Bisht, A.K., 2022. Predicting the potential distribution of Dactylorhiza hatagirea (D. Don) Soo-an important medicinal orchid in the West Himalaya, under multiple climate change scenarios. *PLoS ONE*, 17 (6): e0269673. https://doi.org/10.1371/journal.pone.0269673

Singh, L., Bhatt, I.D., Negi, V.S., Nandi, S.K., Rawal, R.S., Bisht, A.K., 2021. Population status, threats, and conservation options of the orchid Dactylorhiza hatagirea in Indian Western Himalaya. *Regional Environmental Change*, 21: 40. https://doi.org/10.1007/s10113-021-01762-6

Singh, R.M., Chandra, J.T., Rinchen, D., Ayyanadar, A., Prakash, Y.O., 2017. Struggle from subsistence to sustainability and threat to local biodiversity under changing climate: a case study on Ladakh folk agriculture. *Climate Change and Environmental Sustainability*, 5 (1): 59–65. https://doi.org/10.5958/2320- 42X.2017.

00006.0
Smeraldo, S., Di Febbraro, M., Bosso, L., Flaquer, C., Guixé, D., Lisón, F., Meschede, A., Juste, J., Prüger, J., Puig-Montserrat, X., Russo, D., 2018. Ignoring seasonal changes in the ecological niche of non-migratory species may lead to biases in potential distribution models: lessons from bats. *Biodiversity and Conservation*, 27: 2425–2441, https://doi.org/10.1007/s10531-018-1545-7

Sorbe, F., Gränzig, T., Förster, M., 2023. Evaluating sampling bias correction methods for invasive species distribution modeling in Maxent. *Ecological Informatics*, 76: 102124. https://doi.org/10.1016/j.ecoinf.2023.102124

Štípková, Z., Tsiftsis, S., Kindlmann, P., 2024. Is the GBIF appropriate for use as input in models of predicting species distributions? Study from the Czech Republic. *Nature Conservation Research*, 9 (1): 84–95. https://dx.doi.org/10.24189/ncr.2024.008

Stockwell, D., Peterson, A., 2002. Effects of sample size on accuracy of species distribution models. *Ecological Modelling*, 148 (1): 1–13. https://doi.org/10.1016/S0304-3800(01)00388-X

Swarts, N.D., Dixon, K.W., 2009. Terrestrial orchid conservation in the age of extinction. *Annals of Botany*,104 (3): 543–556.https://dx.doi.org/10.1093%2Faob%2Fmcp025

Thakur, N., Kaur, R., 2013. Molecular characterization of Dactylorhiza hatagirea (D. Don) Soó - A critically endangered medicinal orchid. *International Journal of Medicinal and Aromatic Plants*, 3 (2): 184–190.

Thakur, D., Rathore, N., Sharma, M.K., Prakash, O., Chawla, A., 2021. Identification of ecological factors affecting the occurrence and abundance of Dactylorhiza hatagirea (D. Don) Soó in the Himalaya. *Journal of Applied Research on Medicinal and Aromatic Plants*, 20: 100286. https://doi.org/10.1016/j.jarmap.2020.100286

Venne, S., Currie, D.J., 2021. Can habitat suitability estimated from MaxEnt predict colonizations and extinctions? *Diversity and Distributions*, 27: 873–886. https://doi.org/10.1111/ddi.13238

Vij, S.P., 2002. Orchids and tissue culture: current status. In *Role of plant tissue culture in biodiversity conservation and economic development*. Nainital, India: Gyanodaya Prakashan, p. 491–502.

Voldoire, A., Sanchez-Gomez, E., Mélia, D., Decharme, B., Cassou, C., Sénési, S., Valcke, S., Beau, I., Alias, A., Chevallier, M., Déqué, M., 2013. The CNRM-CM5.1 global climate model: description and basic evaluation. *Climate Dynamics*, 40 (10): 2091–2121. https://doi.org/10.1007/s00382-011-1259-y

Wani, I.A., Khan, S., Verma, S. Al-Misned, A., Shafik, H.M., El-Serehy, H., 2022. Predicting habitat suitability and niche dynamics of Dactylorhiza hatagirea and Rheum webbianum in the Himalaya under projected climate change. *Scientific Reports*, 12: 13205 (2022). https://doi.org/10.1038/s41598-022-16837-5

Wani, I.A., Verma, S., Mushtaq, S., Alsahli, A.A., Alyemeni, M.N., Tariq, M., Pant, S., 2021. Ecological analysis and environmental niche modelling of Dactylorhiza hatagirea (D. Don) Soó: A conservation approach for critically endangered medicinal orchid. *Saudi Journal of Biological Sciences*, 28 (4): 2109–2122. https://doi.org/10.1016/j.sjbs.2021.01.054

Warghat, A.R., Bajpai, P.K., Sood, H., Chaurasia, O.P., Srivastava, R.B., 2012. Morphometric analysis of Dactylorhiza hatagirea (D. Don), a critically endangered orchid in cold desert Ladakh region of India. *African Journal of Biotechnology*, 11 (56): 11943–11951. https://doi.org/10.5897/AJB11.4242

Warghat, A.R., Bajpai, P.K., Srivastava, R.B., Chaurasia, O.P., Sood, H., 2013. Population gennetic structure and conservation of small fragmented location of Dactylorhiza hatagirea in Ladakh region of India. *Scientia Horticulturae*, 164: 448–454.

Warren, D.L., Seifert, S.N., 2011. Ecological niche modelling in Maxent: the importance of model complexity and the performance of model selection criteria. *Ecological Applications*, 21: 335–342. http://dx.doi.org/10.2307/29779663

Weldemariam, E.Ch., Dejene, S.W.D., 2021. Predicting invasion potential of Senna didymobotrya (Fresen.) Irwin & Barneby under the changing climate in Africa. *Ecological Processes*, 10: article number 5 (2021). https://doi.org/10.1186/s13717-020-00277-y

Wisz, M.S., Pottier, J., Kissling, W.D., Pellissier, L., Lenoir, J., Damgaard, C.F., Dormann, C.F., Forchhammer, M.C., Grytnes, J.A., Guisan, A., Heikkinen, R.K., Hoye, T.T., Kuhn, I., Luoto, M., Maiorano, L., Nilsson, M.C., Normand, S., Ockinger, E., Schimdt, N.M., Termansen, M., Timmermann, A., Wardle, D.A., Asstrup, P., Svenning, J.C., 2013. The role of biotic interactions in shaping distributions and realised assemblages of species: implications for species distribution modelling. *Biological Reviews*, 88 (1): 15–30. https://doi.org/10.1111/j.1469-185X.2012.00235.x

Xu, D., Zhuo, Z., Wang, R., Ye, M., Pu, B., 2019. Modeling the distribution of Zanthoxylum armatum in China with MaxEnt modeling. *Global Ecology and Conservation*, 19: e00691. https://doi.org/10.1016/j.gecco.2019. e00691

Yang, X.Q., Kushwaha, S.P.S., Saran, S., Xu, J., Roy, P.S. 2013. Maxent modeling for predicting the potential dis tribution of medicinal plant, Justicia adhatoda L. in Lesser Himalayan foothills. *Ecological Engineering*, 51: 83–87. https://doi.org/10.1016/j.ecoleng.2012.12.004

Yi, Y., Cheng, X., Wieprecht, S., Tang, C., 2014. Comparison of habitat suitability models using different habitat suitability evaluation methods. *Ecological Engineering*, 71: 335–345. https://doi.org/10.1016/j.ecoleng.2014.07.034

Yukimoto, S., Adachi, Y., Hosaka, M., Sakami, T., Yoshimura, H., Hirabara, M., Tanaka, T., Shindo, E., Tsujino, H., Deushi, M., Mizuta, R., Yabu, H., Obata, A., Nakano, H., Koshiro, T., Ose, T., Kitoh, A., 2012. A new global climate model of the meteorological research institute: MRI-CGCM3—model description and basic performance. *Journal of Meteorological Society of Japan*. Series II, 90A: 23–64. https://doi.org/10.2151/jmsj.2012-A02

Zlatanov, T., Elkin, C., Irauschek, F., Lexer M.J., 2017.

Impact of climate change on vulnerability of forests and ecosystem service supply in Western Rhodopes Mountains. *Regional Environmental Change*, 17: 79–91. https://doi.org/10.1007/s10113-015-0869-z

Zhong, Y., Xue, Z., Jiang, M., Liu, B., Wang, G., 2021. The application of species distribution modeling in wetland restoration: a case study in the Songnen Plain, Northeast China. *Ecological Indictors*, 121: 107137. https://doi.org/10.1016/j.ecolind.2020.107137

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